AD478040

SSD-TR-66-11

REPORT NO.
TDR-669(6220-10)-1

# Chemistry Effects on RF Attenuatio. During Re-entry

DECEMBER 1965


*Prepared by* F.A. VICENTE
*Plasma Research Laboratory*


*Prepared for* BALLISTIC SYSTEMS AND SPACE SYS[illegible]MS DIVISIONS
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATIO[illegible]
*Los Angeles, California*


LABORATORY OPERATIONS • A[illegible]EROSPACE CORPORATION
C[illegible]NTRACT NO. AF 04(695)-669

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F. A. Vicente
Plasma Research Laboratory

Laboratory Operations
AEROSPACE CORPORATION
El Segundo, California

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Prepared

F. A. Vicente

Approved

R. H. Huddlestone, Head
Re-entry and Plasma
Electromagnetics Department

R. X. Meyer, Director
Plasma Research Laboratory

This technical documentary report has been reviewed and is approved for publication and dissemination. The conclusions and findings contained herein do not necessarily represent an official Air Force position.

For Space Systems Division
Air Force Systems Command

Robert F. Jones
Captain, USAF

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## ABSTRACT

The effects of nonequilibrium and alkali contamination in ablation materials on RF signal attenuation are examined. Sample calculations are made on blunt-nosed lifting, blunt-nosed ballistic, and sharp-nosed ballistic, re-entry vehicles. Results indicate that during the early portion of re-entry flight, nonequilibrium air effects are important but that for ablating vehicles, alkali contaminants predominate in the latter portion of re-entry flight. Lifting re-entry vehicles and sharp-nosed ballistic vehicles are more prone to the alkali effects than blunt-nosed ballistic vehicles.

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CONTENTS



FIGURES

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## NOMENCLATURE

| | | |
|---|---|---|
| e | = | electron |
| $f_t$ | = | transmission frequency, cps |
| g | = | statistical weight |
| M | = | catalytic third body |
| N | = | nitrogen |
| O | = | oxygen |
| P | = | pressure, atmospheres |
| R | = | nose radius, in. |
| S | = | streamline running length, in. |
| T | = | temperature ($^{o}K$) |
| V | = | ionization potential, ev |
| v | = | free stream velocity, fps |
| $W/C_DA$ | = | ballistic coefficient, $lb/ft^2$ |
| X | = | mass fraction of specie |
| x | = | axial body length, in. |
| $Y_s$ | = | shock layer normal, in. |
| y | = | normal distance, in. |
| $\bar{y}$ | = | $y/Y_s$ |
| $\theta_c$ | = | cone angle, deg |

# I. INTRODUCTION

The problem of providing continuous radio communication between re-entry vehicles and ground stations has existed since the first ballistic missile firings. This problem is caused by air, which absorbs energy as it passes through the strong shock wave surrounding a high speed re-entry vehicle. When sufficient energy for dissociation and ionization is available, free electrons occur in the flow and interfere with the radio waves emanating from or going to the re-entry vehicle. The attenuation of radio waves causes the available RF signal to fall below the detection capability of the receiver, causing "blackout."

The transfer of energy from the vehicle to the surrounding fluid depends on both the physical configuration of the vehicle and the chemical composition of the fluid surrounding the vehicle. Shapes of various re-entry vehicles, such as blunt-nosed lifting bodies, blunt-nosed ballistic bodies, and sharp-nosed ballistic bodies are taken into consideration. In Ref. 1, some of the physical parameters affecting attenuation are examined. In that study, however, the chemical effects were not treated. The primary object of this paper, therefore, is to explore the chemical factors significantly affecting the attenuation of RF signals during re-entry.

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# II. CHEMISTRY EFFECTS

Nonequilibrium effects and easily ionized products of heat shield ablation, more than any other chemical factors, greatly alter the plasma composition and hence decrease the signal available at the receiver. In blunt-nosed bodies, nonequilibrium effects cause a thickening of the plasma sheath. This thickening is the result of slow recombination of ionized and dissociated air products as the fluid passes from the nose region to the afterbody.

In sharp-nosed bodies, however, insufficient reaction time exists in the nose region. Consequently, because of nonequilibrium effects, low dissociation and ionization levels are to be expected, and lower electron densities are obtained than for blunt-nosed bodies.

The effects of ablation products, particularly the alkali impurities, are of greater significance than nonequilibrium effects for sharp-nosed vehicles and are of equal significance for blunt-nosed vehicles. An increase in the order of magnitude of electron density within the vehicle boundary layer can be expected as a result of alkali ablation products. Such increases in the available free electrons increase the magnitude and the duration of high RF attenuation.

## A. ANALYSIS OF NONEQUILIBRIUM FLOW

Some insight as to the extent of the nonequilibrium regime and the application to practical problems can be obtained from Fig. 1. The boundaries defining the equilibrium, nonequilibrium, and frozen air flow regimes are based primarily on the recombination rate parameter for air (Ref. 2). The air chemistry boundaries shown in Fig. 1 were determined by assuming a rapid reaction rate which brings the air flow toward equilibrium behind the shock in the highly dense nose cap region. Subsequently, the rapid expansion of the flow around the nose cap and into the afterbody region greatly lowers the density. When this rapid

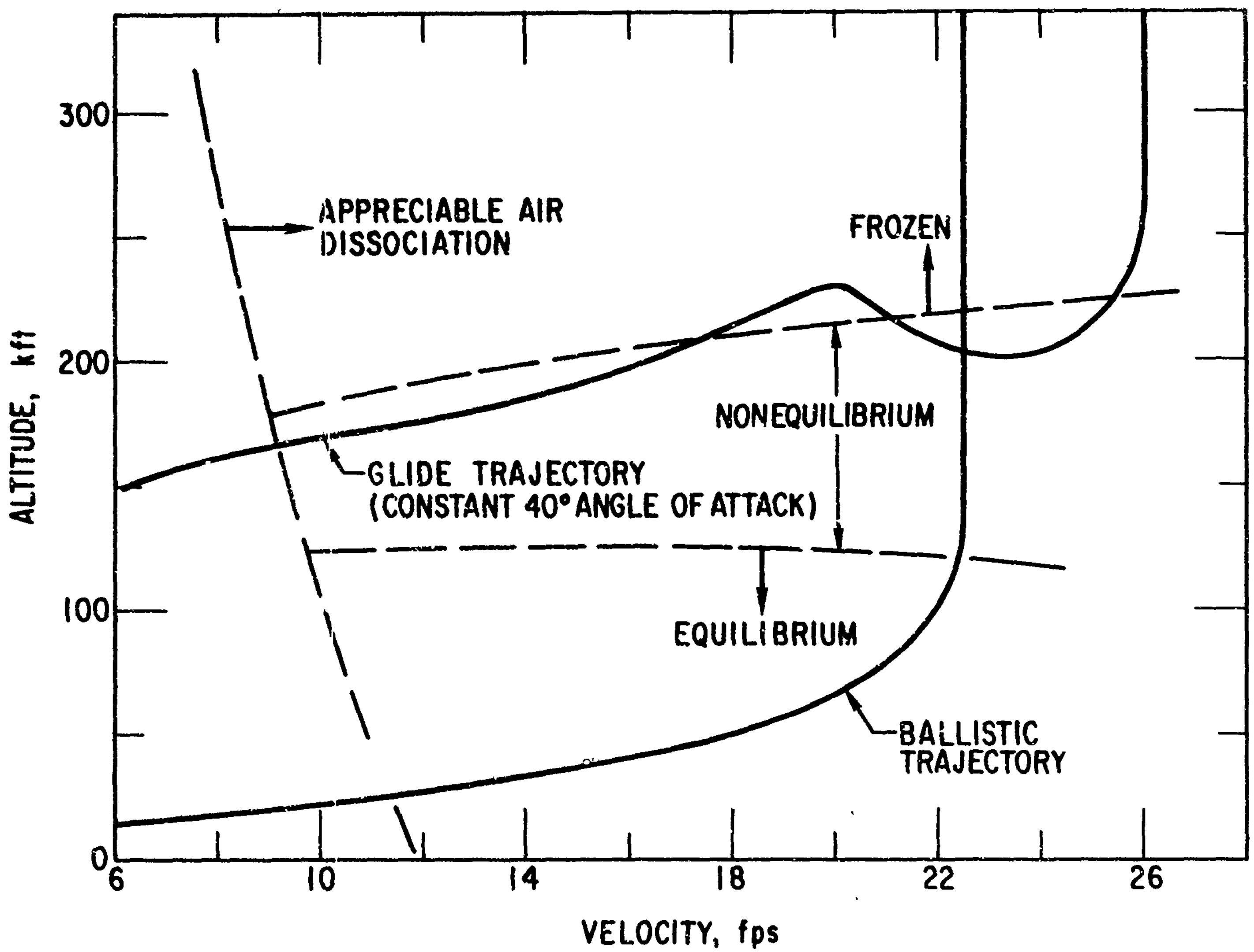


Fig. 1. Air Chemistry Regimes for Lifting and Ballistic Trajectories

expansion is analyzed, using available recombination rates (Ref. 3), the nonequilibrium effects become noticeable. Such a scheme is valid for a blunt-nosed body followed by a region where the air flow is highly expanded. However, if the body is flying at very high angles of attack (say 40 deg.) or is composed of a highly angled afterbody, the flow on the windward surfaces does not necessarily adhere to the criteria shown in Fig. 1.

To analyze the nonequilibrium flow, it is necessary to either solve the inviscid flow field problem by an "exact" nonequilibrium method (Ref. 4), or to first solve the flow by an equilibrium method (Ref. 1) and then to recalculate the chemistry using a stream-tube approach. The latter method, although more tedious, introduces less technical complications and is the method used here. The validity of this method is essentially established for the flight conditions treated here by Bloom and Varglio-Laurin (Ref. 5).

The stream tube approach requires that the pressure-enthalpy-velocity history be prescribed along the streamline. These conditions are obtained from the previously described equilibrium method. In addition, the initial chemistry conditions at the beginning of the streamline are defined. The dissociation and ionization starting conditions can be bounded by considering a frozen or an equilibrium air state. These conditions, together with the appropriate reaction rates (Ref. 6), (both dissociation and recombination) are then sufficient to calculate the nonequilibrium chemistry, including ionization. For simplicity, the chemical-air reactions considered in this paper are limited to

$$O_2 + M \rightleftharpoons O + O + M$$
$$N_2 + M \rightleftharpoons N + N + M$$
$$NO + M \rightleftharpoons N + O + M$$
$$NO + O \rightleftharpoons O_2 + N$$
$$N_2 + O \rightleftharpoons NO + N$$
$$N_2 + O_2 \rightleftharpoons NO + NO$$
$$N + O \rightleftharpoons NO^+ + e$$

## B. ANALYSIS OF IONIZATION IMPURITIES

On the other hand, the effects of the easily ionized alkali impurities in the heat shield ablation material are not so easily treated as the non-equilibrium effects outlined above. The amount of alkali material ablated into the boundary layer depends on the characteristics of the heat shield material. In turn, the type of heat shield chosen for a particular application depends greatly on the type of re-entry expected, e.g., lifting vs. ballistic. Furthermore, the injection of large quantities of material into the boundary layer thickens the boundary layer, which in turn alters the properties of the inviscid layer. It is possible, however, to make simplifying assumptions and to arrive at a first approximation of the alkali distribution within the boundary layer. These assumptions are made so that various percentages of alkali metals in the flow which affect plasma enhancement can be examined.

A useful assumption (Ref. 7) is that the alkali contaminants do not affect the velocity and enthalpy profiles. For example, a simple engineering approximation of the contaminant ablation density would be to assume that the density distribution of alkali materials is a constant percentage of the air density within the boundary layer. The constant percentage, in turn, is determined by ratioing the alkali mass

flow injected into the boundary layer to the air mass flow in the boundary layer at a given station of interest. Other distributions, such as assuming a profile so that no alkali material is present at the edge of the boundary layer, are possible. Calculations have shown (Ref. 8) that in determining RF signal loss, the RF attenuation calculation (being essentially an integrated value) is relatively insensitive to the details of the distribution. Consequently, the simple engineering approximation is used in this paper.

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# III. METHODS OF ANALYSIS

## A. NONEQUILIBRIUM

The air flow in the subsonic-transonic nose region is affected by passing through a strong curved shock. In the nonequilibrium analysis performed here, the method of Lee and Chu (Ref. 9) is used wherein it is assumed that immediately behind the shock the vibrational and rotational degrees of freedom are fully excited but that the chemical dissociation has not started. The seven chemical-air reactions listed in Sect. II-A previously are included in this analysis. The flow in the supersonic regime is analyzed as in Ref. 1 and graphically matched to the analyses for a blunt-nosed body to determine the origin of the streamlines. In the areas where the flow is determined to be in or very near equilibrium, the boundary layer is computed as in Ref. 10.

## B. ALKALI MATERIALS

Alkali material effects are superposed on the boundary layer solution as discussed above. For the trajectories analyzed here, sodium was taken to react in equilibrium with air. For most of the cases considered here, the regions of sufficient ablation to affect the electron density occurred, fortuitously, while the vehicle flow was within or very near to one of the previously defined equilibrium air states. The mixture of alkali material and air, for the simple cases treated here, where the flow is close to equilibrium, can be analyzed by a hand calculation using the Saha equation (Ref. 11) in the form

$$\log_{10}\left(\frac{X^2}{1-X^2}\ P\right) = \frac{-5050V}{T} + 2.5\log_{10}T - 6.5 + \log_{10}\left(\frac{g_e g_a^+}{g_a}\right)$$

Elaborate machine computation procedures (Ref. 12) exist for handling a large number of species, and these agree very well (within 1%) with the simple method. This agreement is attributed to the low energy

levels needed to ionize alkali materials which results in the alkali materials being the major contributors of electrons. The RF attenuation values are then computed by the method of Gold (Ref. 8), with particular attention paid to the plasma thickness in determining the mode of solution, i. e., the approximate Dirac delta solution (Ref. 11) for the sharp-nosed conical body or the more exact exponential profile solution for the blunt-nosed bodies.

## IV. RESULTS OF ANALYSIS

To establish numerical limits for cases of practical interest, three vehicle configurations were chosen for analysis. The first was a blunt-nosed lifting body of moderate L/D, flying a nearly equilibrium glide trajectory. The second and third were a blunt-nosed, conical vehicle and a sharp-nosed, conical vehicle which were flying a high $W/C_DA$ ballistic trajectory. The blunt-nosed lifting body was assumed to present a windward ray which was inclined 40 deg. to the oncoming stream while the blunt-nosed ballistic body could be represented by an afterbody having a 20 deg. cone angle.

### A. NONEQUILIBRIUM EFFECTS

The results of nonequilibrium vs. equilibrium air flow are given in Fig. 2 for an inviscid flow streamline intersecting the boundary layer at S/R = 20. It is observed in the case of the 20 deg. cone angle that the air flow approaches equilibrium in the nose region and then freezes when expanded to the afterbody conditions. The equilibrium calculation shows continuous recombination downstream of the nose to the conical flow values. For the 40 deg. case, however, the nonequilibrium reactions continue past the nose region and equilibrium is approached from below. Of particular interest in the 40 deg. case is the fact that downstream of the nose the flow quickly reaches equilibrium electron density values.

Figure 3 indicates the effect of velocity on nonequilibrium flow for the blunt-nosed body, again computed for an inviscid streamline intersecting the boundary layer at S/R = 20. Since the degree of nonequilibrium depends on the number of collisions among particles at a given thermodynamic state, the increase of air density over a blunt (40 deg.) body tends to drive the flow toward equilibrium. The net effect for such a blunt shape is to increase the air density faster than the vehicle velocity

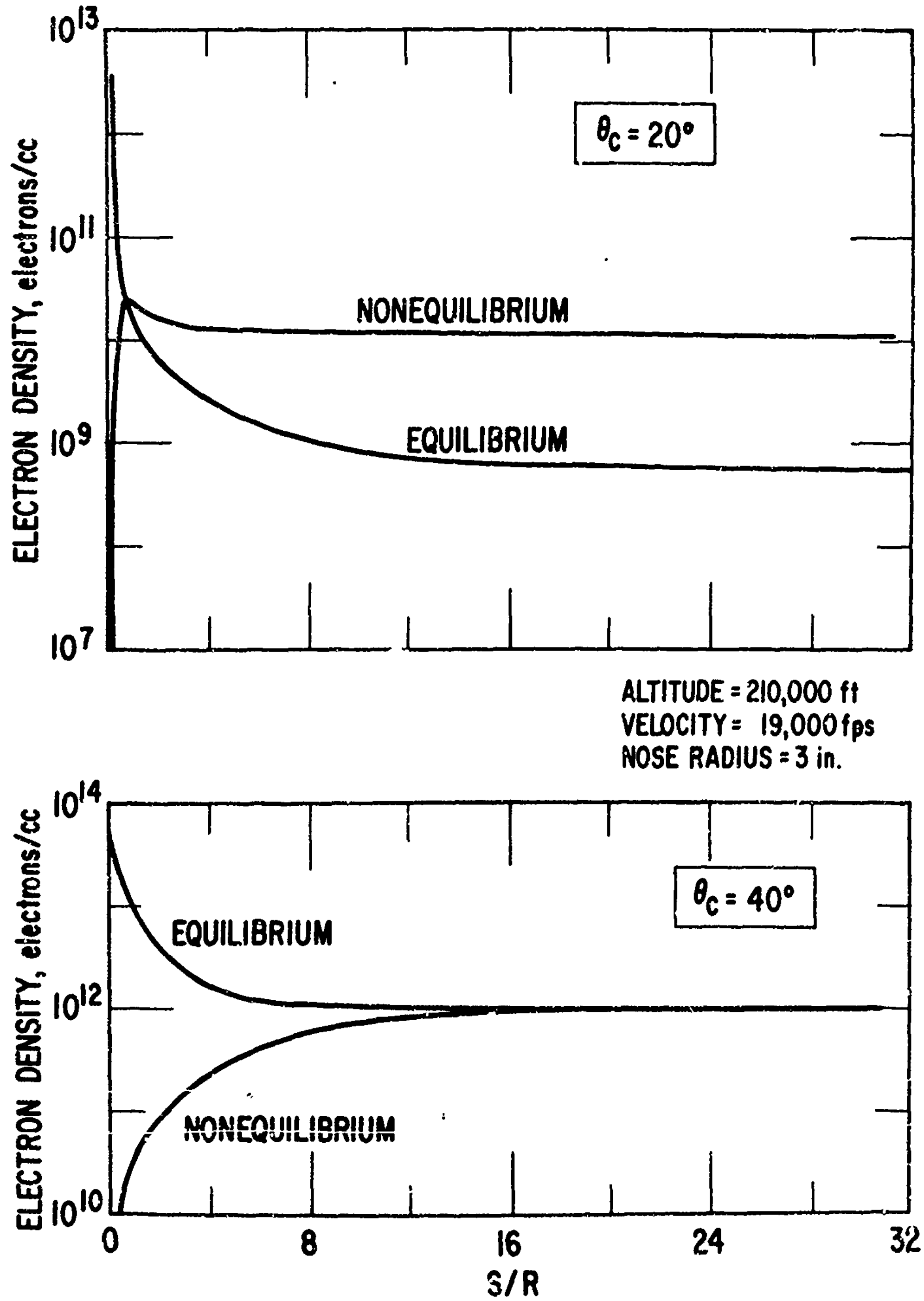


Fig. 2. Nonequilibrium Effects for Different Cone Angles

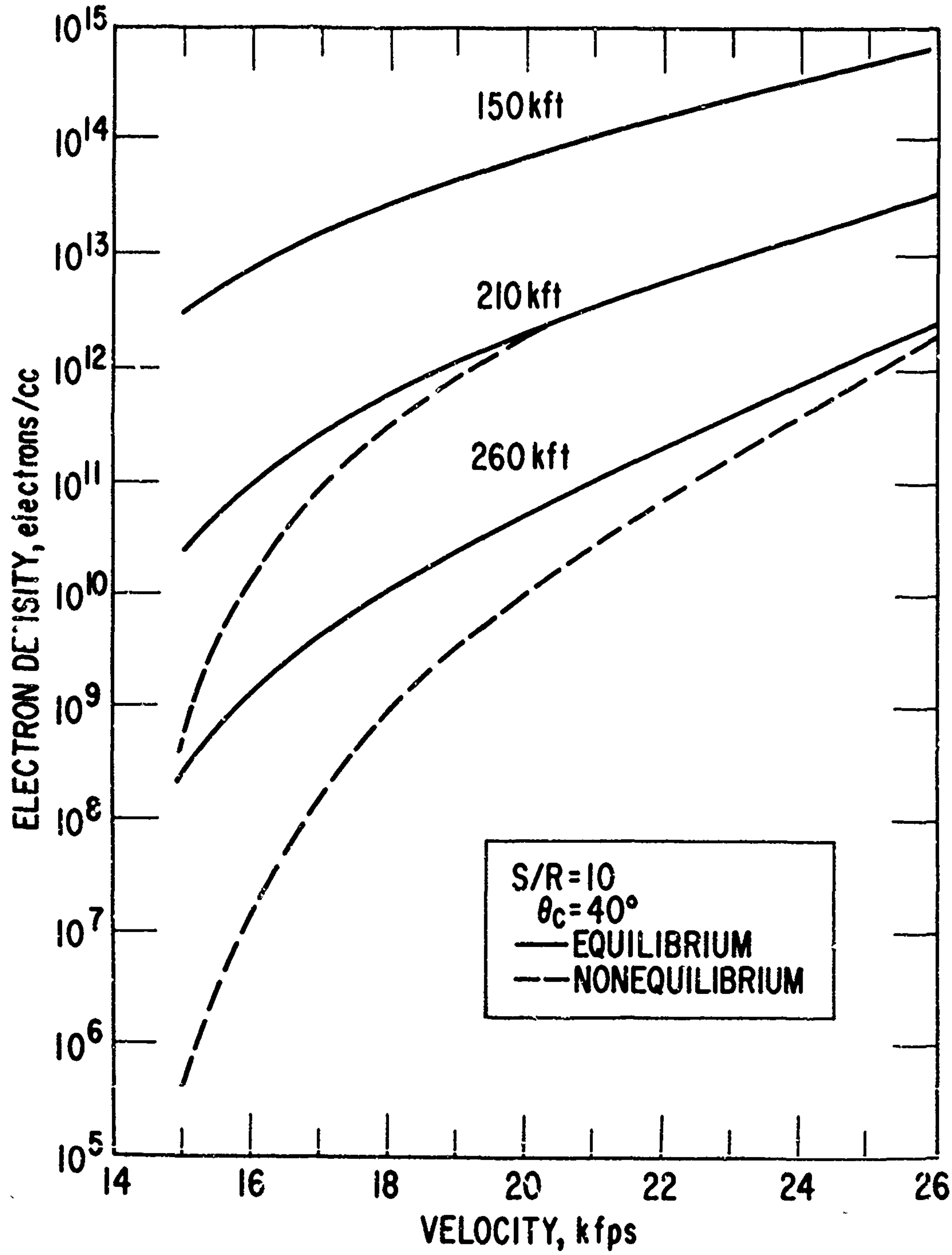


Fig. 3. Nonequilibrium Effects as a Function of Velocity

increases, permitting more collisions among particles in a given time. This causes shorter relaxation times with the resultant flow being forced to equilibrium faster than otherwise expected for a body with a rapid expansion in the afterflow.

## B. ALKALI IMPURITY EFFECTS

The effect of the addition of varying amounts of alkali metals into the flow field (namely the boundary layer) due to ablation of the re-entry heat shield is shown in Fig. 4. It is observed that even a small amount (0.01%) of alkali material is enough to increase the electron density substantially over the clean air case. A trace of alkali material (0.01%) can increase the electron density from one to two orders of magnitude over that of clean air. For large amounts of impurities (1%) several orders of magnitude increase in electron concentration is to be expected. Since the energy required to ionize alkali material is much smaller than that required to ionize air and the dissociation process for alkali compounds tends to be less complicated than for air, the energy available in the flow field can ionize the alkali directly. The addition of impurities in the flow produces a larger number of free electrons which tend to depress the ionization of the air, and, consequently, most of the electrons present in the flow result from the ionization of the impurities rather than from air.

Typical electron distribution profiles through the flow field are given in Figs. 5 and 6 for a blunt-nosed body and a sharp-nosed body respectively. Note that, due to the engineering assumptions regarding the effect of ablation materials in the boundary layer for the blunt-nosed body, a discontinuity appears in the profile. The effect of alkali addition, however, is of more interest in this paper; errors of engineering assumptions do not significantly change the attenuation results. Of greater importance is the fact that the peak electron density in the flow for both the blunt-and sharp-nosed cases is in excess of an order of magnitude over the clean air case—even for small amounts of impurities.

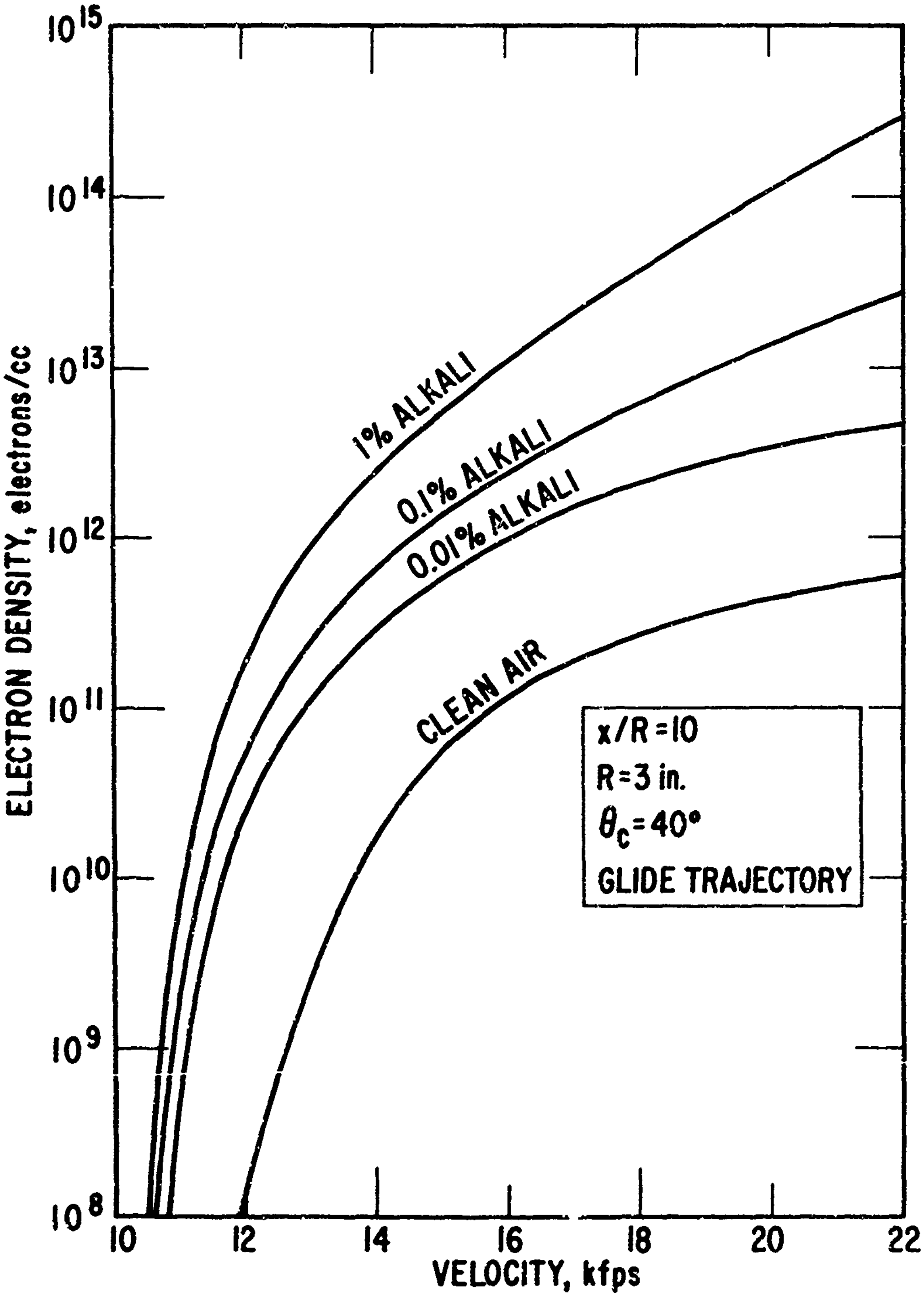


Fig 4. Alkali Effects on Electron Density

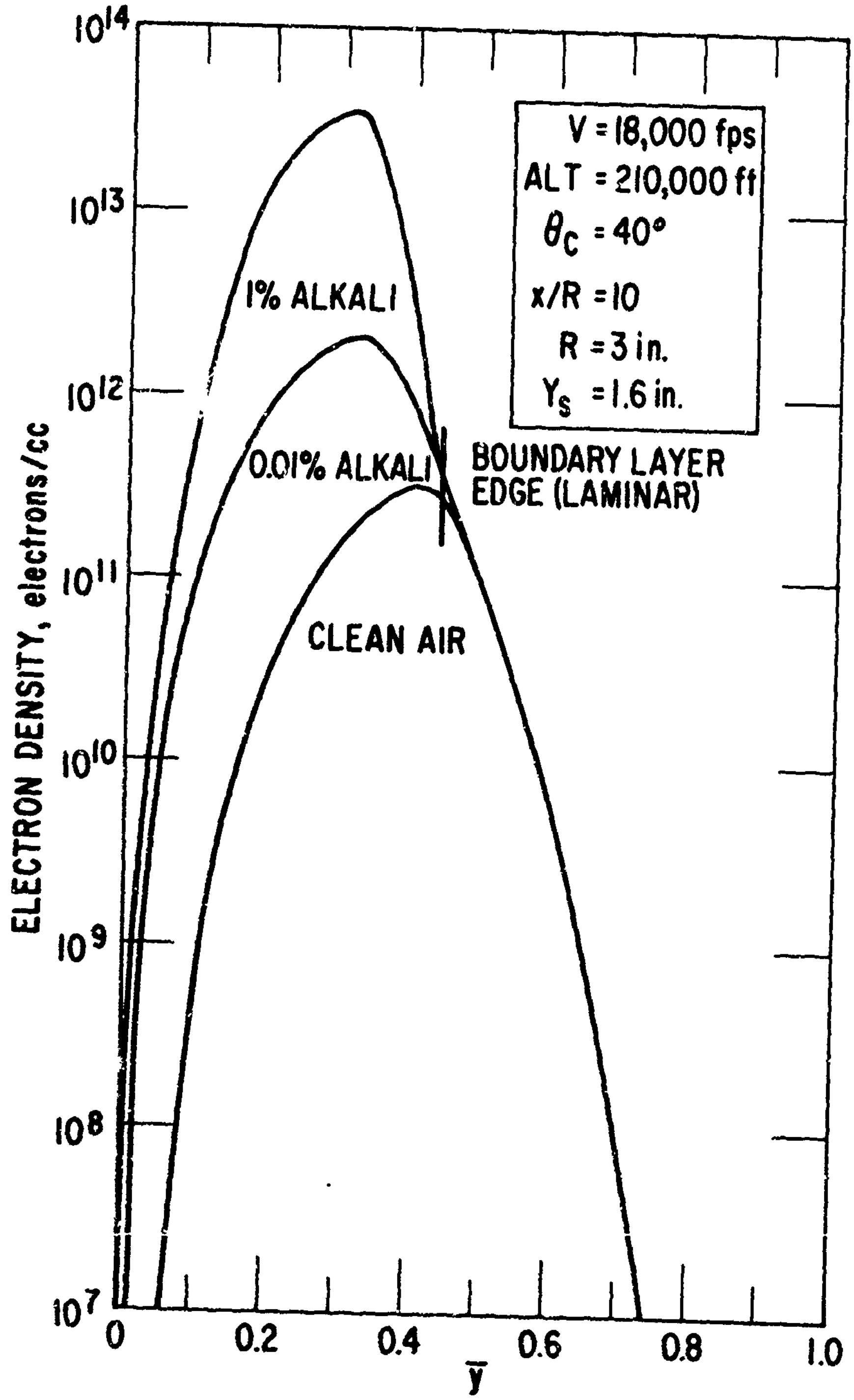


Fig. 5 Electron Density Distribution Through Shock Layer (blunt body)

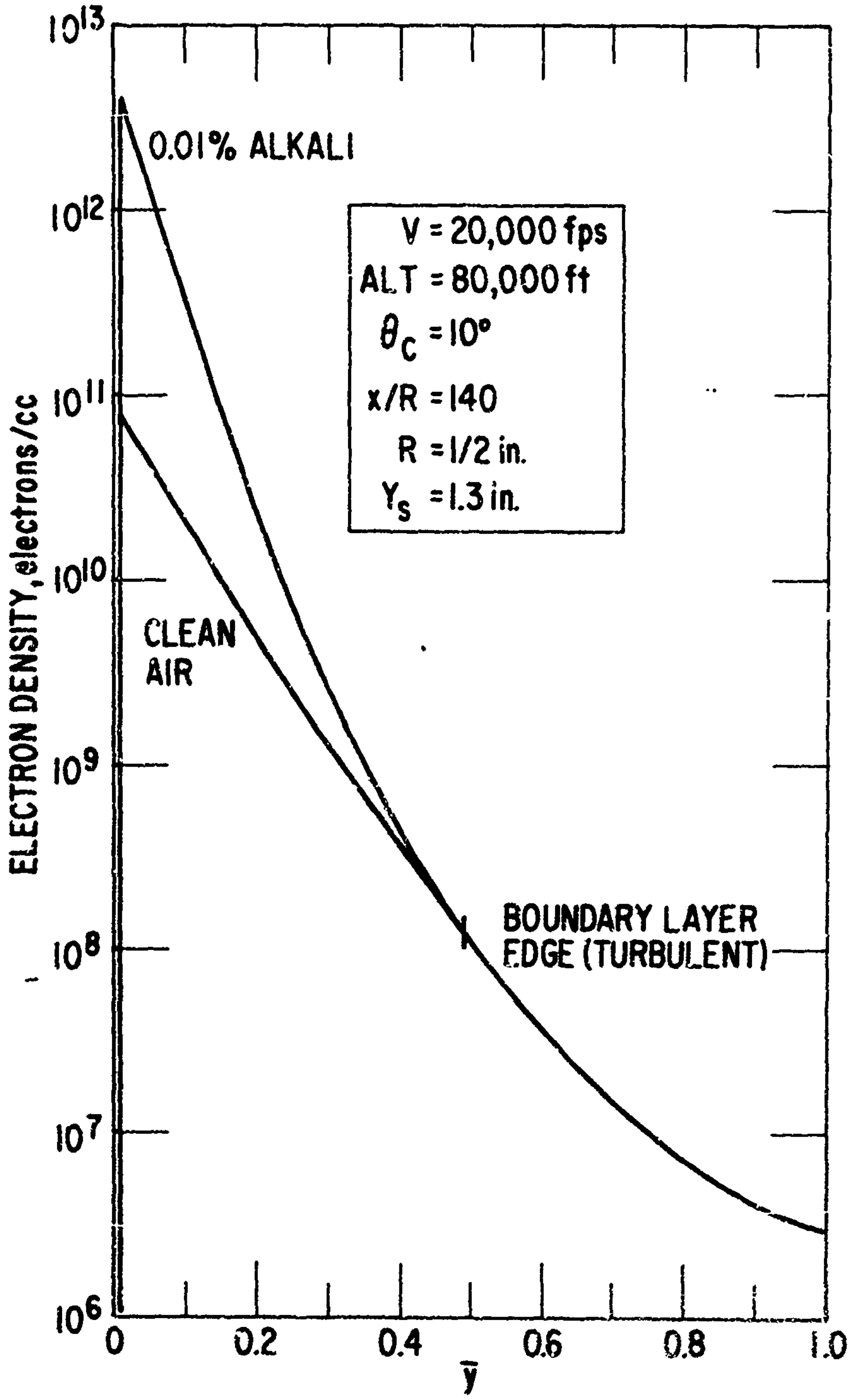


Fig. 6. Electron Density Distribution Through Shock Layer (sharp body)

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## V. CALCULATIONS OF RF ATTENUATION

Using the electron densities calculated from Figures 5 and 6, it is possible to compute the RF attenuation values which are presented for different vehicles in Figs. 7, 8, and 9. The calculation method for attenuation is the same as that of Ref. 1. Figure 7 indicates the persistence of high attenuation levels for long periods of flight time for a blunt-nosed lifting body. The effects of nonequilibrium air chemistry predominate for the initial periods of high RF attenuation. Ablation begins after the vehicle is well into re-entry and its effects predominate over the middle and latter portions of flight. Because lifting vehicles may cover hundreds or even thousands of miles during re-entry, the problem becomes critical from a data acquisition and a ground station operation standpoint. As indicated in Fig. 7, for an arbitrary attenuation limit of 20 dB defining blackout, a small inclusion of alkali material (0.01%) leads to a loss of transmission time of 160 sec over that expected for clean air. Similarly, a large amount of alkali impurities (1%) leads to an additional loss of 105 sec for a total loss of 265 sec over clean air expectations.

The ballistic blunt-nosed body results (Fig. 8), on the other hand, lead to higher total attenuation values but shorter additional times of high RF attenuation because of alkali impurities. A small amount of alkali material only delays rebroadcast by 2 sec, while a large amount of impurity leads to a loss of 4 sec. Results presented in Fig. 9 for a sharp-nosed vehicle, however, indicate that transmission might be possible (on the arbitrary basis of 20 dB) for small amounts of alkali impurities while large amounts of impurities will cause severe attenuation, leading to possible loss of signal.

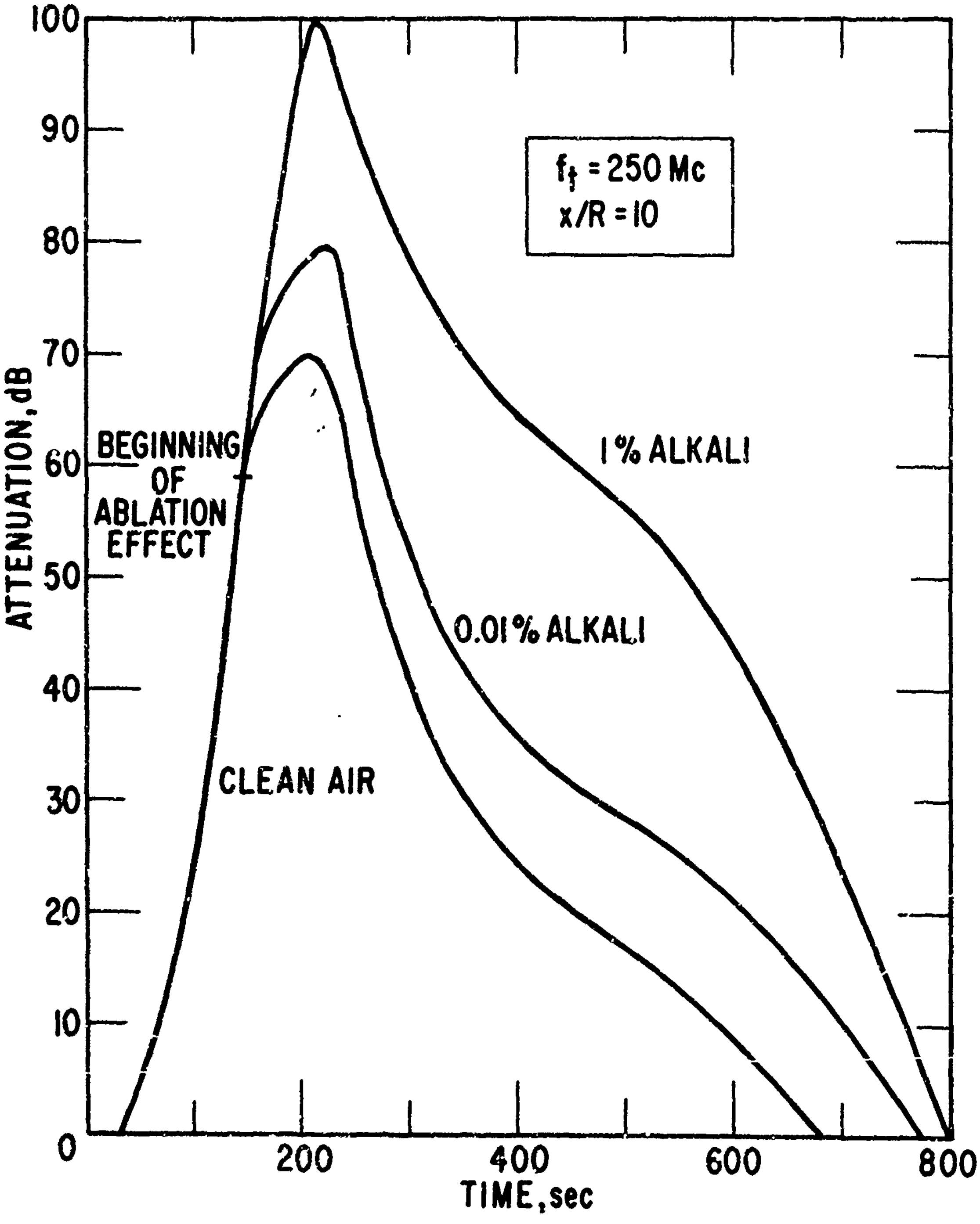


Fig. 7. Attenuation Profile for Lifting Body Glide Trajectory

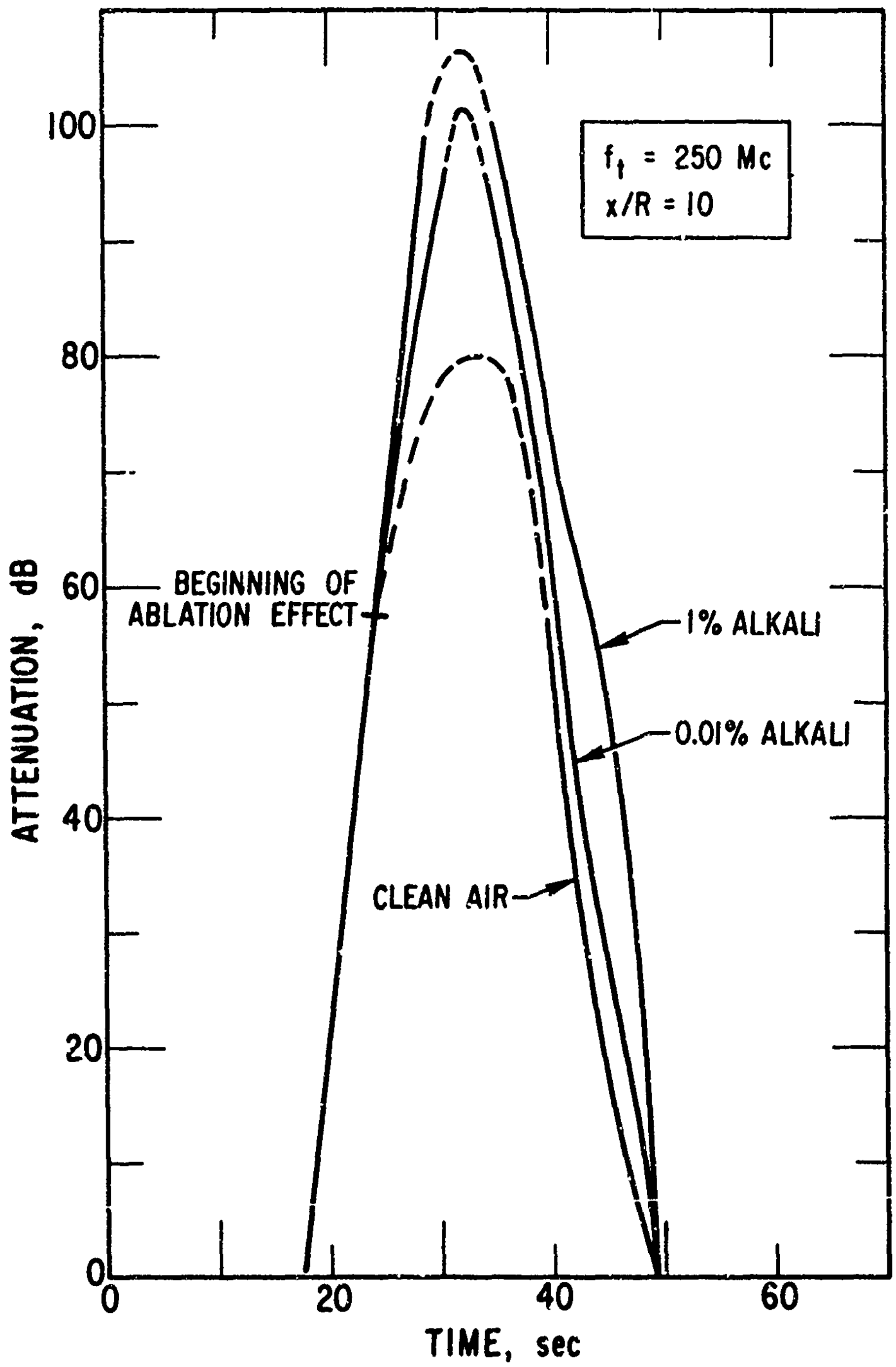


Fig. 8. Attenuation Profile for Blunt Ballistic Re-entry

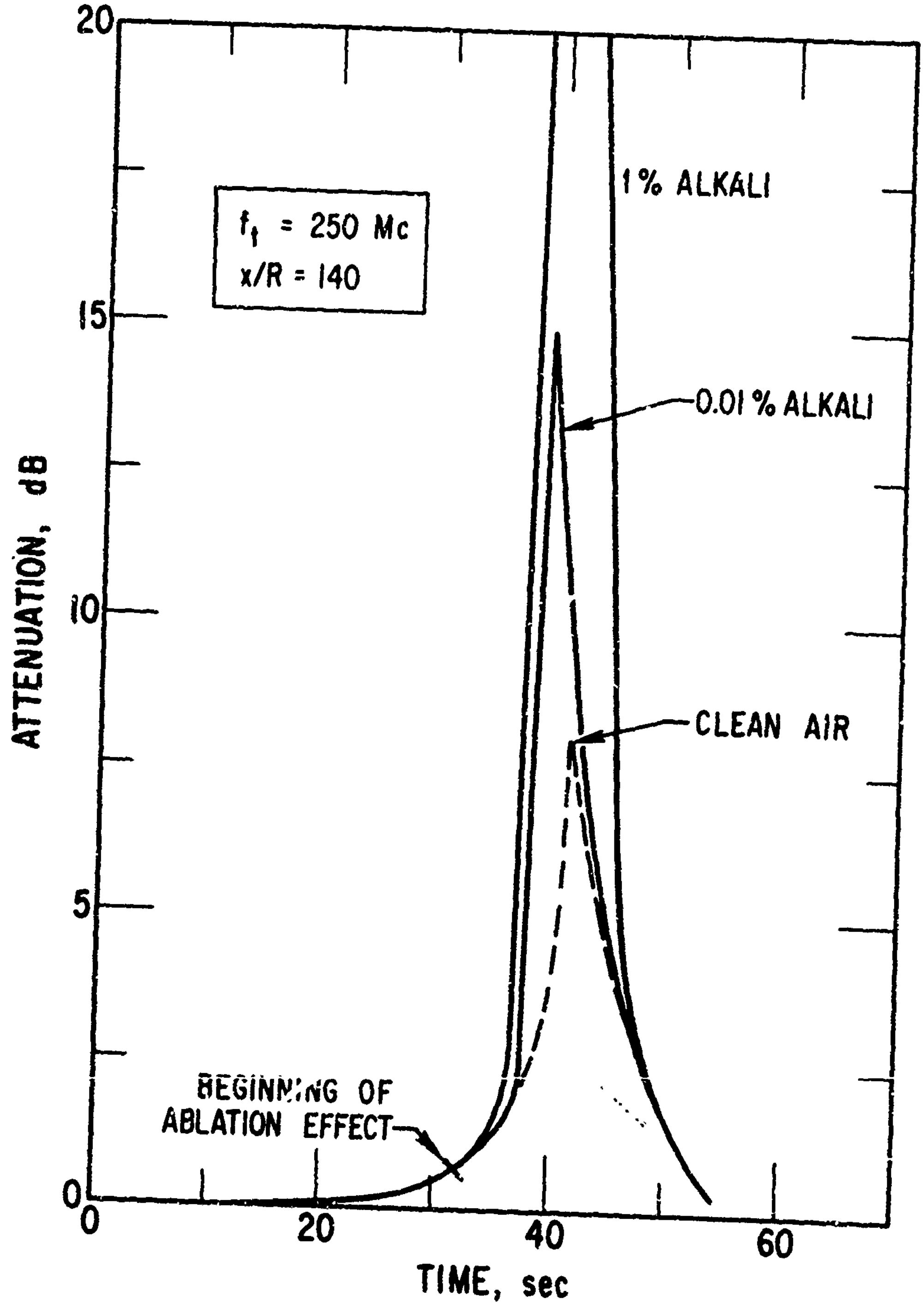


Fig. 9. Attenuation Profile for Sharp Ballistic Body

## VI. CONCLUSIONS

For blunt-nosed vehicles, the effects of chemistry on RF attenuation indicate that during the early portion of flight, while the vehicle is at relatively high altitudes, nonequilibrium effects in the air flow are important, and that if the vehicle is covered by an ablating heat-shield containing alkali impurities, the ablating chemistry will predominate in the middle and latter portion of re-entry. This suggests that nonequilibrium effects cause "blackout" and dominate it through the first period of re-entry, and ablation chemistry (ionization of alkali impurities) dominates through emergence from "blackout."

In addition, the results presented in this paper indicate that the problem of RF attenuation, including the effects of ablation products, is more critical for blunt-nosed lifting vehicles and sharp-nosed ballistic vehicles than for a blunt-nosed ballistic vehicle. Alkali impurities can extend the "blackout" period in blunt-nosed lifting bodies for over four minutes, and excessive impurity levels can seriously impair radio transmission from sharp-nosed, ballistic vehicles.

## REFERENCES


1. Vicente, F. A., "Effects of Various Re-entry Vehicle Parameters on Radio Frequency Attenuation," J. Spacecraft, Vol. 1, No. 6, Nov-Dec 1964.

2. Whalen, R. J., "Viscous and Inviscid Nonequilibrium Gas Flows," JAS Vol. 29, No. 19, October 1962.

3. Wray, K. L., "Chemical Kinetics of High-Temperature Air," ARS Paper No. 1975-61, August 1961.

4. Sedney, R., et al., "Characteristic Calculation of Nonequilibrium Flows," BRL Report No. 1173, April 1962.

5. Vaglio-Laurin, R. and Bloom, M. H., "Chemical Effects in External Hypersonic Flows," ARS Paper No. 1976-61, August 1961.

6. Wray, K. L., "Chemical Kinetics of High Temperature Air," ARS Paper No. 1975-61, August 1961.

7. Kane, J. J., "Nonequilibrium Sodium Ionization in Laminar Boundary Layers," Aerospace Corp. Report TDR-269(S4810-22)-2, April 1964.

8. Gold, R. R., "Reflection and Transmission of Electromagnetic Waves From Inhomogeneous Magneto-active Slabs," Aerospace Corp. Report TDR-169(3230-11)TN-12, March 1962.

9. Lee, R. H. and Chu, S. T., "Nonequilibrium Inviscid Flow About Blunt Bodies," Aerospace Corp. Report TDR-269(4560-10)-2, January 1964.

10. Levinsky, E. S. and Fernandez, F. L., "Approximate Nonequilibrium Air Ionization in Hypersonic Flows Over Sharp Cones," Aerospace Corp. Report TDR-269(S4810-60)-1, November 1963.

11. Cobine, J. D., Gaseous Conductors, Dover Publications, Inc., New York, 1958.

12. Vale, A. J., "The Aerospace Corporation Computer Program for the Solution of Multielement Chemical Equilibrium," Aerospace Corp. Report TDR-69(2240-51)TR-2, July 1963.

UNCLASSIFIED

Security Classification

# DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

| | |
|---|---|
| 1 ORIGINATING ACTIVITY (Corporate author)<br>Aerospace Corporation<br>El Segundo, California | 2a REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b GROUP |

3 REPORT TITLE

CHEMISTRY EFFECTS ON RF ATTENUATION DURING RE-ENTRY

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

5 AUTHOR(S) (Last name, first name, initial)

Vicente, Francis A.

| | | |
|---|---|---|
| 6 REPORT DATE<br>December 1965 | 7a TOTAL NO. OF PAGES<br>29 | 7b. NO. OF REFS<br>12 |

| | |
|---|---|
| 8a CONTRACT OR GRANT NO.<br>AF 04(695)-669 | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>TDR-669(6220-10)-1 |
| b PROJECT NO.<br>c.<br>d | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)<br>SSD-TR-66-11 |

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| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Ballistic and Space Systems Division<br>Air Force Systems Command<br>Los Angeles, California |

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14 KEY WORDS

RF Attenuation
Nonequilibrium Effects
Ablation Effects
Alkali Impurities
Re-entry Vehicles
Lifting Re-entry Vehicles
Flow Fields
Chemical Effects

Abstract (Continued)

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